Forest Ecology and Management 320 (2014) 1–5

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Effects of two types of Ca fertilizer on sugar maple nutrition, vigor and growth after 7 years

Jean-David Moore *, Rock Ouimet

Direction de la recherche forestière, Ministère des Ressources naturelles du Québec, 2700 rue Einstein, Québec, Québec G1P 3W8, Canada

ARTICLE INFO

Article history:
Received 19 December 2013
Received in revised form 11 February 2014
Accepted 15 February 2014
Available online 15 March 2014

Keywords:
Sugar maple
Liming
Ca fertilizer
Dieback
Nutrition
Growth

ABSTRACT

Sugar maple (*Acer saccharum* Marsh., hereafter SM) dieback has been of concern in many stands of northeastern North America for decades. In acidic, base-poor forest soils, this phenomenon has often been attributed to calcium (Ca) deficiency. Corrective measures such as dolomitic lime addition ($CaMg(CO_3)_2$) have been tested to restore SM vitality in these ecosystems. However, few studies have evaluated the effect of Ca addition alone on SM. Furthermore, liming experiments have showed that the Mg content of lime could induce a nutritional antagonism which hinders potassium (K) uptake. This may have limited the response of SM to dolomitic lime application. To address these issues, two calcium fertilizers with negligible Mg content ($CaCO_3$ and $CaSO_4{\cdot}2H_2O$) were applied at rates of 1, 2 and 4 t Ca ha^{-1} on SM trees. After 7 years, foliar Ca nutrient concentrations of treated trees increased in both Ca treatments, reaching published concentration ranges for healthy SM trees. These increases were greater than those observed after a similar period in two nearby experiments in which $CaMg(CO_3)_2$ and $CaCO_3$ were used at comparable or lower doses. Also, no nutrient antagonism was detected in the present study. Tree crown vigor and basal area growth were improved by the Ca treatments, but the magnitude of the growth response for trees treated with the $CaCO_3$ fertilizer was far less than in the other nearby experiment where $CaCO_3$ was also used. This strongly suggests that Mg nutrition is not a limiting factor in this ecosystem. The comparatively lower growth response of trees to Ca treatments in this study is unclear, but better growth conditions at the studied site, compared to the two other nearby experiments, may have played a role in this phenomenon. Long-term monitoring of these experiments seems warranted to clarify these issues.

1. Introduction

Over the last decades, evidence of base cation depletion in soils with a low acid-buffering capacity has been reported in forests of northeastern North America (Houle et al., 1997; Likens et al., 1998; Johnson et al., 2008). This phenomenon has been attributed, at least in part, to acid deposition (Houle et al., 1997; Likens et al., 1998; McLaughlin, 1998; Sharpe, 2002; Bailey et al., 2005; Long et al., 2009).

Sugar maple (*Acer saccharum* Marsh., hereafter SM) is known to be very sensitive to soil acidity, aluminum toxicity, and poor soil Ca availabilty (Wilmot et al., 1995; Bailey et al., 2004; Long et al., 2011; Moore et al., 2012). In Quebec, Duchesne et al. (2002) have shown that SM decline and the associated growth reduction could be related, at least in part, to soil acidification and increased acid deposition. In this context, several base cation fertilization experiments were established on sites with acidic, base-poor soils (e.g.: Wilmot et al., 1996; Long et al., 2011; Ouimet et al., 2008; Moore et al., 2012). Improved SM nutrition, growth and vigor after base cation addition demonstrated the link between base cation deficiency and SM vitality. However, relatively few studies have evaluated the effect of Ca addition alone on SM (Juice et al., 2006; Huggett et al., 2007; Ouimet et al., 2008). Moreover, improvement of SM vitality in liming studies occurred despite declines in foliar K (Long et al., 2011; Moore et al., 2012) below the sufficiency threshold established for this element (see Moore and Ouimet, 2010 for a review). This decrease in foliar K in these liming studies is likely due to the high Mg content of dolomitic lime (12%) used in these experiments, which caused a K–Mg antagonism. This phenomenon is well known for SM and appears when the availability is much greater for Mg than for K (Mengel and Kirkby, 1980; Ouimet and Camiré, 1995; Ouimet et al., 1996).

In this study, we tested the hypothesis that Ca fertilizers with a negligible Mg content (<1% Mg for $CaSO_4{\cdot}2H_2O$ and $CaCO_3$) could improve SM nutrition, vigor and growth without causing foliar K deficiency in the longer term (7 years). In the short term ($\leqslant$3 years), Ca and Mg nutrition, crown vigor and basal area growth

* Corresponding author. Tel.: +1 (418) 643 7994; fax: +1 (418) 643 2165.
E-mail address: jean-david.moore@mrn.gouv.qc.ca (J.-D. Moore).

http://dx.doi.org/10.1016/j.foreco.2014.02.017
0378-1127/

had increased for both Ca treatments, and no nutrient antagonism had been observed (Moore and Ouimet, 2010). However, the growth response was of smaller magnitude than in two Ca addition experiments established nearby ($CaMg(CO_3)_2$: Moore and Ouimet, 2006; $CaCO_3$: Ouimet et al., 2008; Table 1). This study should help to verify the longer-term effect of these Ca fertilizers on SM nutrition, vigor and growth.

2. Material and methods

2.1. Site description

The experimental stand (46°57′N, 71°40′W) is located in the Duchesnay Experimental Forest, approximately 50 km northwest of Quebec City (Quebec, Canada), bordering the Lake Clair experimental Watershed (LCW). Site elevation varies between 270 and 390 m and the average slope is approximately 10%. Mean annual temperature is 3.4 °C and annual precipitation (1971–2000) totals 1300 mm. Forest stands are mainly uneven-aged, with vegetation dominated by SM, yellow birch (*Betula alleghaniensis* Britt.) and American beech (AB) (*Fagus grandifolia* Ehrh.) (basal areas of 21, 3, and 3 $m^2\ ha^{-1}$, respectively). Dominant and codominant SM trees are 85–130 years old, with an average height of 20 m and average diameter at breast height (DBH) of 28 cm. According to the *Canadian System of Soil Classification* (Canada Soil Survey Committee, 1998), the soil is classified as a stony, sandy loam Orthic Ferro-Humic Podzol. The humus type is of moder, and the surface deposit is a very acidic (Houle et al., 1997, 2002) and stony glacial till derived from the granitic gneiss bedrock of the Canadian Shield.

2.2. Stand conditions and disturbance history

The LCW is among the catchments in northeastern North America where acid deposition continues to acidify soils, leading to relatively high net soil Ca losses (Watmough et al., 2005). Over the period 1994–2009, atmospheric NO_3^-, NH_4^+, SO_4^{2-}, and H^+ loads in bulk deposition were estimated at 19, 5, 20 and 0.4 kg $ha^{-1}\ year^{-1}$, respectively. Neither severe insect defoliation nor frost or ice damage was observed in the area recently. Relatively short summer drought episodes did occur in 1995 and in 2002, but they did not cause lasting growth reductions. The last forest cutting in the experimental area was a thinning in the 1940s.

At Duchesnay, SM poor nutrition (Ca and Mg), vigor, and growth have been reported over the last decade (Duchesne et al., 2002; Ouimet et al., 2008; Moore and Ouimet, 2010; Moore et al., 2012). The low Ca availability in this ecosystem is probably attributable to the combination of high levels of acid deposition, significant Ca leaching, and relatively low Ca replenishment through mineral weathering in the soil (Houle et al., 1997; Ouimet and Duchesne, 2005).

Before treatment application in 2002, mean (±sd) foliar concentrations of Ca (5500 ± 1600 mg kg^{-1}), Mg (1200 ± 300 mg kg^{-1}) and Mn (800 ± 300 mg kg^{-1}) of the 63 selected SM trees were considered low, according to SM nutritional values in other studies (Moore and Ouimet, 2010). At the same time, conspicuous signs of dieback remained prevalent at the LCW (Ouimet et al., 2008; Moore et al., 2012).

Table 1
Comparison of control trees for the three Ca addition studies at Duchesnay.

	This study (after 7 years)	Moore and Ouimet, 2006 (after 10 years)	Ouimet et al., 2008 (after 10 years)
Foliar concentrations			
Ca (mg kg^{-1})	5212	4604	4540
Mg (mg kg^{-1})	1119	1083	980
BAI (Fig. 3)	High	Low	Low
Crown dieback (%)	4	30	2

2.3. Experimental design

In a maple stand adjacent to the LCW, 63 SM trees were selected in June 2002. To ensure a long-lasting experimental trial, trees were chosen without major trunk defects or crown dieback. They also had to be at least 15 m apart. Mean (± standard deviation) DBH of these subjects was 33.2 ± 8.2 cm (2002), and their basal area increment (BAI) was 12.2 ± 1.6 $cm^2\ year^{-1}$ (1990–2002). Granulated calcium carbonate ($CaCO_3$) or gypsum ($CaSO_4{\cdot}2H_2O$) fertilizers (commercial grade) were applied manually in June 2002 in a 5-m radius around SM trees, at a rate of 1, 2 and 4 t ha^{-1} of Ca, that is, 2.8, 5.6 and 11.1 t ha^{-1} of $CaCO_3$ or 3.7, 7.4 and 14.8 t ha^{-1} of $CaSO_4$. On the acidic forest floors in the area (pH = 3.5 ± 0.5; Moore et al., 2012; Ouimet et al., 2008), gypsum (dissolution constant $\log K_{25\,°C} = -4.64$) should be more stable than calcium carbonate ($\log K_{25\,°C} = 9.74$) (Lindsay, 1979), but it should also dissolve more quickly because the compound is hydrated.

Each treatment was applied randomly to 9 replicate trees during the first week of September 2002, before leaf fall. This experimental setup was directly adjacent to a dolomitic liming trial implemented in 1994 (the "dolomitic lime experiment", Moore et al., 2000; Moore and Ouimet, 2006) and close to another fertilizer trial implemented in 1990 (the "acidification/alkalinization experiment" Ouimet et al., 2008).

2.4. Sampling

Foliage was sampled before treatment in early August 2002, then in August of 2003, 2004, 2005 and 2009. This time of year corresponds to a period of stable foliar concentration preceding foliar coloration (Duchesne et al., 2001). Foliage was collected from each tree with a telescopic pole pruner at mid-crown on two opposite branches. Crown dieback was assessed in 2002 and 2009 on the same day as foliage sampling, by estimating the percentage of missing crown foliage (5% class intervals) from careful visual inspection. Foliar nutrient concentrations were used to evaluate nutritional status.

In November 2009, two increment cores were taken from opposite sides of each tree at breast height to measure tree radial growth. Annual ring width was measured using WinDendro version 6.1D software (Régent Instruments Inc., 1998) and validated with signature rings. Ring width values were converted to BAI (in cm^2) using the following equation:

$$\mathrm{BAI}_t = \pi(R_t^2 - R_{t-1}^2)$$

where R is the tree radius (cm), and t is the year of tree-ring formation. One of the two cores from two control trees were removed because of highly abnormal growth rings and associated wood discoloration in recent years, suggesting that these cores were taken near a stem flaw or a previous core sample.

2.5. Chemical analyses

For each tree, a foliage sample of approximately 40 leaves was dried at 65 °C, then ground to ⩽250 μm. Following Kjeldahl digestion of a 500 mg subsample, nitrogen (N) concentration was determined by colorimetry (Kjeltec Tecator 1030 autoanalyzer), and P, K, Ca, Mg, and Mn concentrations were measured by inductively-coupled plasma-atomic emission spectroscopy (Perkin Elmer Plasma Model 40). Standard reference material used for the

inter-laboratory comparison programs were always within 5% of the reference values.

2.6. Statistical analyses

Foliar concentrations and mean stem BAI were analyzed for the 2003–2009 period and for 2009 only, using a two-way analysis of variance (ANOVA), with Ca source and Ca dose as main treatments. For the foliar analyses, the corresponding 2002 covariable was used, when applicable. To account for tree growth variability between treatments before liming, the BAI for 2003–2009 and for 2009 only were adjusted with the pretreatment BAI, using each tree's average BAI for 1998–2002 as a covariable. Individual trees were considered as a random factor. The statistical analyses were performed using the SAS MIXED procedure (SAS Institute, 2002). The data for crown dieback proportion in individual trees in 2009 were analyzed using the general linear model (glm function) of the MASS R package (Venables and Ripley, 2002) with the logit link and the quasi-binomial distribution to correct for underdispersion. The crown dieback of individual trees in 2002 was used as covariable in the analysis. Nutrition, crown dieback and growth data were examined using contrasts to compare treated *vs.* control groups, and orthogonal polynomial contrasts to separate the linear and quadratic components of the trend across treatments.

3. Results

3.1. Foliar nutrient status

Seven years after their application, both Ca treatments improved foliar Ca concentrations of SM ($CaCO_3$: quadratic effect, $P = 0.001$; $CaSO_4$: linear effect, $P < 0.001$; Table 2). The relative increase in foliar Ca was greater in trees fertilized with $CaCO_3$ (104%) than $CaSO_4$ (44%) (Table 2 and Fig. 1). Decreases of foliar N (linear effect, $P = 0.039$), Mg (linear effect, $P = 0.021$), were observed for the $CaSO_4$ treatment only. Decreases of foliar Mn concentrations were observed for both treatments ($CaSO_4$: all rates *vs.* control, $P = 0.046$; $CaCO_3$: linear effect, $P < 0.001$). Neither type of Ca fertilizer had an effect on foliar P and K concentrations ($P \geqslant 0.631$). Also, foliar concentrations after Ca treatments (Table 2) were within published ranges for healthy SM (Moore and Ouimet, 2010), except for Mg (in 2009, Mg means were 1.2 g kg^{-1} for $CaSO_4$ treatments and 0.9 g kg^{-1} $CaCO_3$ treatments), which were generally below or in the lower part of the range for healthy SM. Foliar weight per 10 leaves, their specific surface area, and their density (weight divided by surface area) were not different among treatments ($P \geqslant 0.519$).

Table 2
Unadjusted foliar N, P, K, Ca, Mg and Mn concentrations (mg kg^{-1}) for controls and trees treated with $CaCO_3$ or $CaSO_4{\cdot}2H_2O$ (t Ca ha^{-1}) fertilizer, 7 years after treatments, and *p*-values for results of ANOVA and contrast analysis. *P* values $\leq$ 0.05 are shown in bold.

Treatment (t Ca ha^{-1})	Foliar concentrations N	P	K	Ca	Mg	Mn
Control	18,211	1489	6589	5212	1119	772
$CaCO_3$ (1)	17,200	1478	6500	9480	1097	706
$CaCO_3$ (2)	18,989	1609	6956	11,139	1227	567
$CaCO_3$ (4)	18,536	1468	7136	11,226	1190	402
$CaSO_4$ (1)	17,089	1532	7044	5269	809	587
$CaSO_4$ (2)	16,356	1349	6433	7539	948	608
$CaSO_4$ (4)	16,833	1537	7067	9769	914	706
Model P values						
Treatment comparison	**0.047**	0.631	0.990	**<0.001**	**0.001**	**0.005**
Contrast P values						
$CaCO_3$ linear	0.864	0.262	0.568	**<0.001**	0.826	**<0.001**
$CaCO_3$ quadratic	0.730	0.158	0.811	**0.001**	0.707	0.878
$CaSO_4$ linear	**0.039**	0.863	0.413	**<0.001**	**0.021**	0.320
$CaSO_4$ quadratic	0.304	0.786	0.881	0.701	**0.047**	0.086
$CaCO_3$ *vs.* control	0.593	0.912	0.588	**<0.001**	0.814	**0.006**
$CaSO_4$ *vs.* Control	**0.013**	0.851	0.636	**0.018**	**0.002**	**0.046**
$CaCO_3$ *vs.* $CaSO_4$	**0.005**	0.911	0.927	**<0.001**	**<0.001**	0.261

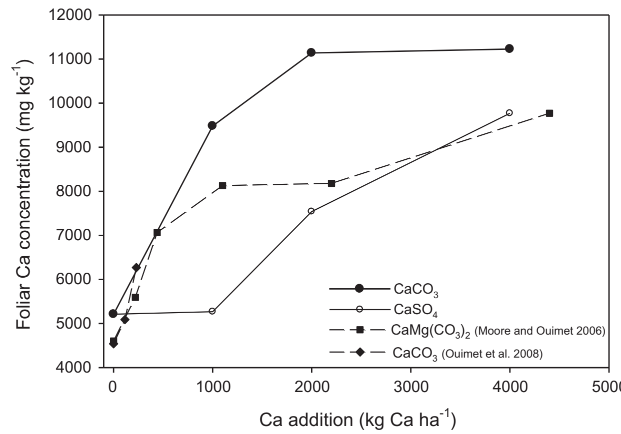

Fig. 1. Mean foliar Ca concentrations of sugar maple at Duchesnay following additions of $CaCO_3$ (CC; this study, after 8 years), $CaSO_4{\cdot}2H_2O$ (CS; this study, after 7 years), $CaMg(CO_3)_2$ (Lime; Moore and Ouimet, 2006, after 10 years), and $CaCO_3$ (CC; Ouimet et al., 2008, after 10 years).

3.2. Crown dieback and basal area growth

Before treatment application, mean crown dieback of SM was 4.7% ($CI_{95\%} = 3.3–6.5\%$). Seven years after treatment, crown dieback seemed to have increased for the control trees (mean = 10.2%, $CI_{95\%} = 5.2–19.0\%$) compared to the Ca-fertilized trees (all Ca-treatments confounded: mean = 4.1%, $CI_{95\%} = 2.2–7.7\%$). This difference was nearly statistically significant ($P = 0.078$). The crown dieback measured at the beginning of the experiment was related partly to its value seven years later ($r = 0.261$, $P = 0.027$).

Significant or near-significant increases in BAI were observed for Ca-fertilized trees (doses combined, and compared to controls), 7 years (combined) after Ca treatments ($CaCO_3$:+36%, $P = 0.014$; $CaSO_4$:+37%, $P = 0.011$) as well as in 2009 ($CaCO_3$:+25%, $P = 0.063$; $CaSO_4$:+28%, $P = 0.058$) (Fig. 2). However, fertilizer doses neither affected BAI themselves nor tree crown dieback ($P \geqslant 0.093$).

4. Discussion

4.1. Foliar nutrient status

After 7 years, the relative increase in foliar Ca was greater in trees fertilized with $CaCO_3$ than $CaSO_4$ (Table 2 and Fig. 1). Lower foliar Mg and manganese (Mn) concentrations were also observed in trees treated with $CaSO_4$. These differences seem to indicate that adding sulfur to the site's soil may have caused cation release and leaching (Lee and Weber, 1982). The foliar Ca increase observed after the $CaCO_3$ treatment was also greater than in the nearby dolomitic lime experiment (Moore and Ouimet, 2006), after a similar period of time and application rate (Fig. 1). Given that the foliage was sampled the same year in both experiments, the difference in response might be related to competition between Ca and Mg ion uptake (Ouimet et al., 1996). Indeed, both cations are mainly transported from the soil to the roots by mass-flow (Barber, 1962).

Given that both Ca sources may have increased the live biomass of SM trees in a same way (see BAI and vigor responses), the different responses in foliar N concentrations observed for the two Ca

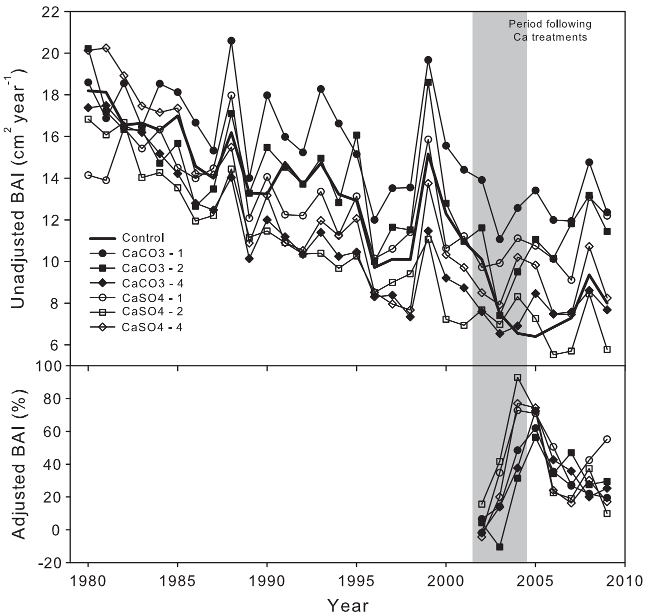

Fig. 2. Unadjusted and adjusted (with 1998–2001 pre-treatment BAI and relative to the control trees) basal area growth of sugar maple after $CaCO_3$ and $CaSO_4{\cdot}2H_2O$ application (t Ca ha^{-1}) in June 2002. The shaded area represents the first 3 years after treatments (Moore and Ouimet 2010).

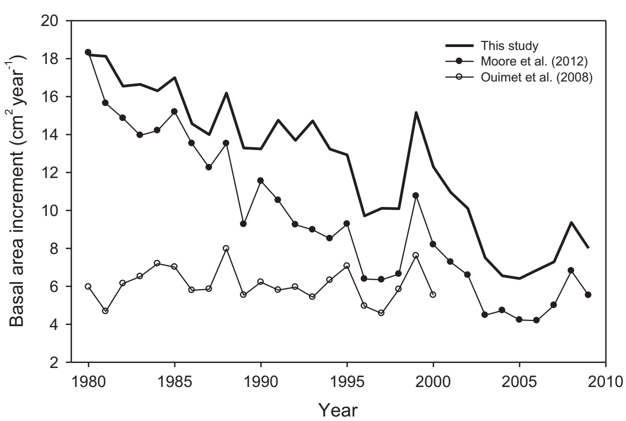

Fig. 3. Mean basal area increment of control sugar maple trees in the three Ca-addition experiments at Duchesnay.

fertilizers in this experiment could be due to their different effects on soil N cycle. Although this was not tested in this study, the decrease of foliar N concentrations following $CaSO_4$ fertilization could be explained by a decrease in soil N availability due to a decrease in nitrification and an increase in NH_4–N leaching caused by gypsum (Belkacem and Nys, 1995), resulting in a lower N uptake by trees. The $CaCO_3$ effect on N nutrition was somewhat ambiguous because of the distinct responses observed between the acidification/alkalinization experiment (Ouimet et al., 2008) and this study. While no effect of the $CaCO_3$ treatment was observed on foliar N concentration in this study, lower foliar N was noted in SM trees for the nearby $CaCO_3$ treatment. This difference between the two experiments can be explained by a greater N dilution in trees due to a better response of the live biomass of SM to the $CaCO_3$ treatment in the nearby experiment.

A decrease in foliar Mn concentrations was observed with increasing $CaCO_3$ rates after 7 years (Table 2). A similar result was noted in other mid- and long-term studies using carbonate fertilizers, which generally increase soil pH (Long et al., 2011; Moore and Ouimet, 2006; Moore et al., 2012). However, this mid-tern result contrasts with the absence of short-term effect of $CaCO_3$ that we initially observed (Moore and Ouimet, 2010). This suggests that, in the conditions prevailing after the treatments, it took longer than 3 years for $CaCO_3$ treatments to affect foliar Mn concentrations. Moreover, the decrease in foliar Mn concentrations 7 years after the $CaSO_4$ addition contrasts with the short-term increase in foliar Mn observed after this treatment (Moore and Ouimet, 2010). This shows that the likely "salt effect", by which the added Ca displaces Mn on the soil exchange sites (Moore and Ouimet, 2010), leading to higher Mn concentrations in the soil solution and increased uptake by SM through mass-flow, no longer existed 7 years after $CaSO_4$ addition.

4.2. Tree health and growth

Seven years after the beginning of this experiment, the rate of crown dieback among control SM trees increased from 4% to 10%. This is however much lower than the high dieback rate (~40%) observed at the same time in untreated SM trees in the dolomitic lime experiment adjacent to this study area. Nonetheless, BAI of control trees in both areas tended to decline over the last three decades, though this trend was stronger in the dolomitic lime experiment (from 18.3 ± 1.9 (SE) to 5.5 ± 1.7 cm^2 $year^{-1}$, Fig. 3) than in this study (from 18.2 ± 3.5 to 8.9 ± 1.9 cm^2 $year^{-1}$). Duchesne et al. (2003) have shown that a constant decrease in BAI growth rate eventually leads to visual symptoms of crown dieback, and previous studies have shown that the long-lasting predisposing factors prevailing at Duchesnay (low soil base cation saturation, Ca-poor soil, high acid deposition levels) can lead to SM dieback even without strong triggering factors (Moore et al., 2012). Sooner or later, it is therefore likely that the declining BAI growth trend observed for control trees in the present study (Fig. 2) is symptomatic of increasing visual symptoms of dieback in this area. The crown dieback rate at the other nearby $CaCO_3$ site was also low (Table 1) when the last measurements were made (2000), but an increase of crown dieback rate was observed since that time at Duchesnay (Moore et al., 2012).

Both Ca fertilizers improved basal area growth of SM after 7 years (Fig. 2). However, this response was less that of treated trees in the adjacent dolomitic lime experiment, and in the other nearby acidification/alkalinization experiment (Table 3), for

Table 3
Comparison of treated trees for the three Ca addition studies at Duchesnay.

	This study (after 7 years)	Moore and Ouimet, 2006 (after 10 years)	Ouimet et al., 2008 (after 10 years)
Treatment (kg Ca ha^{-1})	$CaCO_3$ (dose 1000, 2000, 4000)	$CaMg(CO_3)_2$ (dose 220, 1100, 2200, 4400)	$CaCO_3$ (dose 230)
Treatment effects			
Ca foliar concentration	Increase	Increase	Increase
Mg foliar concentration	Unchanged	Increase	Unchanged
Crown dieback	Unchanged	Decrease	Unchanged
BAI (%)	+21, +37, +28, respectively	+85, +137, +65, +69, respectively	+203

similar or even lower doses and after a similar period of time. The lower BAI response after $CaCO_3$ fertilization in this study is surprising, given the greater increase in foliar Ca concentration in treated trees compared to the two other nearby studies (Table 3), and the lack of foliar K–Mg antagonism for treated SM trees. Moreover, the BAI increase observed after 7 years was less than after 3 years (Fig. 2). Interestingly, the BAI in 2005 was the lowest value measured for control trees in this experiment (Fig. 3), at a value close to the range where strong BAI responses were noted in the two nearby experiments at Duchesnay. This suggests that a combination of low thresholds for nutrition and growth must be reached before the trees may react (Table 2 and Fig. 3). Moreover, a greater BAI improvement was observed in the acidification/alkalinization experiment (Ouimet et al. 2008) after the addition $CaCO_3$ fertilizer, without any improvement of Mg concentration in foliage of treated trees (Table 3). These observations strongly suggests that Mg nutrition does not limit SM growth in the present study, and contradicts previous assertions that Mg is important for SM growth and vigor in this area (Bernier and Brazeau 1988; Côté et al. 1993; Moore and Ouimet 2010). Long-term monitoring of these experiments seems warranted to clarify these issues. Moreover, the present study and the other $CaCO_3$ study do not support the hypothesis that Ca fertilizers with low Mg content, by preventing antagonism between K and Mg, will induce a better growth response than dolomitic lime.

5. Conclusion

Seven years after the application of $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ fertilizers to Ca-deficient SM trees in a northern hardwood stand, improvement of foliar Ca status and tree growth and vigor was still noticeable. However, the growth response was far less than in a nearby experiment where similar product was used. The results strongly suggest that Mg does not limit SM growth in this ecosystem. Also, the comparatively lower growth response of trees to Ca treatments in this study is unclear, but better growth conditions of the studied site, compared to the two other nearby experiments, may have play a role in this phenomenon. Long-term monitoring of these experiments seems warranted to clarify these issues.

Acknowledgements

This research was funded by the *Ministère des Ressources naturelles du Québec* (Project No. 112310063). We wish to thank Benoît Toussaint and Jacques Martineau for field assistance, Isabelle Auger for statistical advice, and the staff of the Inorganic and Organic Chemical Lab for the numerous chemical analyses.

References

Bailey, S.W., Horsley, S.B., Long, R.P., Hallett, R.A., 2004. Influence of edaphic factors on sugar maple nutrition and health on the Allegheny Plateau. Soil Sci. Soc. Am. J. 68, 243–252.
Bailey, S.W., Horsley, S.B., Long, R.P., 2005. Thirty years of change in forest soils of the Allegheny Plateau, Pennsylvania. Soil Sci. Soc. Am. J. 69, 681–690.
Barber, S.A., 1962. A diffusion and mass-flow concept of soil nutrient availability. Soil Sci. 93, 39–49.
Belkacem, S., Nys, C., 1995. Consequences of liming and gypsum top-dressing on nitrogen and carbon dynamics in acid forest soils with different humus forms. Plant Soil 173, 79–88.
Bernier, B., Brazeau, M., 1988. Magnesium deficiency symptoms associated with sugar maple dieback in a Lower Laurentians site in southeastern Quebec. Can. J. For. Res. 18, 1265–1269.
Canada Soil Survey Committee, 1998. The Canadian system of soil classification. Publ. 1646, third ed. Ottawa, Ontario.
Côté, B., Hendershot, W.H., O'Halloran, I., 1993. Response of sugar maple to seven types of fertilization in southern Quebec: growth and nutrient status. In: Huettl/Mueller-Dombois (Eds.). Forest decline in the Atlantic and Pacific region, Springer-Verlag, Berlin. pp. 162–174.
Duchesne, L., Ouimet, R., Camiré, C., Houle, D., 2001. Seasonal nutrient transfers by foliar resorption, leaching, and litter fall in a northern hardwood forest at Lake Clair Watershed, Quebec, Canada. Can. J. For. Res. 31, 333–344.
Duchesne, L., Ouimet, R., Houle, D., 2002. Basal area growth of sugar maple in relation to acid deposition, stand health, and soil nutrients. J. Env. Qual. 31, 1676–1683.
Duchesne, L., Ouimet, R., Morneau, C., 2003. Assessment of sugar maple health based on basal area growth pattern. Can. J. For. Res. 33, 2074–2080.
Houle, D., Paquin, R., Camiré, C., Ouimet, R., Duchesne, L., 1997. Response of the Lake Clair Watershed (Duchesnay, Quebec) to change in precipitation chemistry (1988–1994). Can. J. For. Res. 27, 1813–1821.
Houle, D., Duchesne, L., Moore, J.-D., Richer-Laflèche, M., Ouimet, R., 2002. Soil and tree-ring chemistry response to liming in a sugar maple stand. J. Env. Qual. 31, 1993–2000.
Huggett, B.A., Schaberg, P.G., Hawley, G.J., Eagar, C., 2007. Long-term calcium addition increases growth release, wound closure, and health of sugar maple (Acer saccharum) trees at the Hubbard Brook Experimental Forest. Can. J. For. Res. 37, 1692–1700.
Johnson, A.H., Moyer, A., Bedison, J.E., Richter, S.L., Willig, S.A., 2008. Seven decades of calcium depletion in organic horizons of Adirondack forest soils. Soil Sci. Soc. Am. J. 72, 1824–1830.
Juice, S.M., Fahey, T.J., Siccama, T.G., Driscoll, C.T., Denny, E.G., Eagar, C., Cleavitt, N.L., Minocha, R., Richardson, A.D., 2006. Response of sugar maple to calcium addition to northern hardwood forest. Ecology 87, 1267–1280.
Lee, J.J., Weber, D.E., 1982. Effects of sulfuric acid rain on major cation and sulfate concentrations of water percolating through two model hardwood forests. J. Env. Qual. 11, 57–64.
Likens, G.E., Driscoll, C.T., Buso, D.C., Siccama, T.G., Johnson, C.E., Lovett, G.M., Fahey, T.J., Reiners, W.A., Ryan, D.F., Martin, C.W., Bailey, S.W., 1998. The biogeochemistry of calcium at Hubbard Brook. Biogeochemistry 41, 89–173.
Lindsay, W.L., 1979. Chemical Equilibria in Soils. John Wiley and Sons, New York, p. 449.
Long, R.P., Horsley, S.B., Hallett, R.A., Bailey, S.W., 2009. Sugar maple growth in relation to nutrition and stress in the northeastern United States. Ecol. Appl. 19, 1454–1466.
Long, R.P., Horsley, S.B., Hall, T.J., 2011. Long-term impact of liming on growth and vigor of northern hardwoods. Can. J. For. Res. 41, 1295–1307.
McLaughlin, D., 1998. A decade of forest tree monitoring in Canada: evidence of air pollution effects. Environ. Rev. 6, 151–171.
Mengel, K., Kirkby, E.A., 1980. Potassium in crop production. Adv. Agron. 33, 59–110.
Moore, J.D., Ouimet, R., 2006. Ten-year effect of dolomitic lime on the nutrition, crown vigor and growth of sugar maple. Can. J. For. Res. 36, 1834–1841.
Moore, J.-D., Ouimet, R., 2010. Effects of two Ca fertilizer types on sugar maple vitality. Can. J. For. Res. 40, 1985–1992.
Moore, J.-D., Camiré, C., Ouimet, R., 2000. Effects of liming on the nutrition, vigor and growth of sugar maple at the Lake Clair watershed, Quebec, Canada. Can. J. For. Res. 30, 725–732.
Moore, J.-D., Ouimet, R., Duchesne, L., 2012. Soil and sugar maple response 15 years after dolomitic lime application. For. Ecol. Manage. 281, 130–139.
Ouimet, R., Camiré, C., 1995. Foliar deficiencies of sugar maple stands associated with soil cation imbalances in the Quebec Appalachians. Can. J. Soil Sci. 75, 169–175.
Ouimet, R., Duchesne, L., 2005. Base cation weathering and release rates from soils and watersheds in three calibrated forest catchments on the Canadian Shield, Quebec, Canada. Can. J. Soil Sci. 85, 245–260.
Ouimet, R., Camiré, C., Furlan, V., 1996. Effect of soil K, Ca and Mg saturation and endomycorrhization on growth and nutrient uptake of sugar maple seedlings. Plant Soil 179, 207–216.
Ouimet, R., Moore, J.-D., Duchesne, L., 2008. Effects of experimental acidification and alkalinization on soil and growth and health of *Acer saccharum* Marsh. J. Plant Nutr. Soil Sci. 171, 858–871.
Régent Instruments Inc., 1998. WinDendro version 6.3. Université du Québec à Chicoutimi, Chicoutimi, Québec, Canada.
SAS Institute, 2002. SAS/STAT User's Guide, Version 9.1. SAS Publishing, Cary, NC, USA.
Sharpe, W.E., 2002. Acid deposition explains sugar maple decline in the east. Bioscience 52, 4–5.
Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S, fourth ed. Springer, New York, p. 495.
Watmough, S.A., Aherne, J., Alewell, C., Arp, P.A., Bailey, S.W., Clair, T.A., Dillon, P., Duchesne, L., Eimers, C., Fernandez, I., Foster, N., Larssen, T., Miller, E.K., Mitchell, M., Page, S., 2005. Sulphate, nitrogen and base cation budgets at 21 forested catchments in Canada, the United States and Europe. Env. Sci. Technol. 109, 1–36.
Wilmot, T.R., Ellsworth, D.S., Tyree, M.T., 1995. Relationships among crown condition, growth, and stand nutrition in seven northern Vermont sugarbushes. Can. J. For. Res. 25, 386–397.
Wilmot, T.R., Ellsworth, D.S., Tyree, M.T., 1996. Base cation fertilization and liming effects on nutrition and growth of Vermont sugar maple stands. For. Ecol. Manage. 84, 123–134.